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Coordination of Reaching in Children with Spastic Hemiparetic Cerebral Palsy Under Different Task Demands

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Coordination of reaching with the impaired and non-impaired arm in 10 children with spastic hemiparetic cerebral palsy (SHCP) was examined in a stationary ball and moving ball context. Kinematic data on trunk, arm, and wrist movements, and coordination patterns between joint angles of elbow, shoulder, and trunk, were analyzed to determine how reaching was influenced by impairment and object motion. Results showed longer deceleration time and movement time and greater trunk contribution following decreased elbow and shoulder excursion when reaching with the impaired arm compared to the non-impaired arm. The coordination of joint angle pairs showed little linearity for the impaired arm, indicating more segmented movements of shoulder and elbow. It was also found that coordination patterns between elbow, shoulder, and trunk displayed less similarity when reaching with the impaired arm compared to the non-impaired arm in both stationary and moving ball conditions. Regardless of the timing constraints, children with SHCP could make successful interceptions using the impaired arm, indicating that they coordinated and controlled the degrees of freedom within their own functional possibilities.

Key Words: degrees of freedom, coordination, reaching, children, spastic hemiparetic cerebral palsy, angle-angle plots, postural adjustments

Children with mild to moderate spastic hemiparetic cerebral palsy (SHCP) are capable of performing movements with their impaired and non-impaired arms (Utley & Sugden, 1998; Van der Weel & Van der Meer, 1991; Van der Weel, van der Meer, & Lee, 1996). For example, Utley and Sugden (1998) showed that SHCP children can perform unimanual (impaired arm) and bimanual (impaired and non-impaired arms) reaching, grasping, and touching tasks at speed. As most children with SHCP are not able to fully stretch the impaired arm, however, or have

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problems flexing/extending the knee or foot on the impaired side of their body, they are constrained to find solutions within their own action capabilities. To date, there has been limited study on the intra-limb and inter-limb coordination of these movements in children with SHCP, but similar to work on adults with SHCP or hemiparesis, compensatory strategies are likely to include a change in the recruitment of the available degrees of freedom or moving with a slower speed and longer duration. For instance, when adults with SHCP or hemiparesis reach for an object with the impaired arm they often show an increased variability of the wrist trajectory, increased trunk involvement, longer movement times, and a stereotyped order of shoulder-elbow recruitment (Archaumbault, Pigeon, & Feldman, 1999; Levin, 1996; Steenbergen, Hulstijn, Lemmens, & Meulenbroek, 2000). The stereotyped shoulder-elbow recruitment is reflected by an initial combined elbow/shoulder movement followed by an isolated elbow extension. This modified coordination between the elbow and shoulder of the impaired arm produces lower cross-correlation coefficients compared to the non-impaired arm, and has been considered as evidence of more segmented upper arm movements (Levin, 1996).

Rehabilitation research has shown that task context can be of great importance in improving movement performance in individuals with movement disorders or disabilities (Majsak, Kaminski, Gentile, & Flanagan, 1998; Volman, Wijnroks, & Vermeer, 2002; Wu, Trombly, Lin, & Tickle-Degnen, 2000). In participants with cerebral palsy, it has been shown that functional and relevant task contexts are more effective for movement planning, increasing the range of motion, and performing smoother movements (Steenbergen, Meulenbroek, & Rosenbaum, 2004; Volman et al. 2002; Wu et al. 2000). For instance, Volman et al. (2002) demonstrated that reaching movements in adults became faster and smoother, with more symmetric velocity profiles when a task involved reaching to press a switch that illuminated a light compared to when a task involved reaching simply to press a marker. Similarly, Van der Weel and Van der Meer (1991) showed that the range of motion of the impaired arm increased when the task required children with SHCP to bang a drum with their hand compared to a condition where they were instructed to "move as far as you can with your arm."

As well as the relevance of task context, the nature of the timing constraints (i.e., whether the task is internally or externally paced) has been shown to influence the motor response of individuals with movement disorders or disabilities. Van Thiel, Meulenbroek, Hulstijn, and Steenbergen (2000) reported that adults with SHCP exhibited a significantly shorter reaction time and movement time when hitting a moving object compared to a stationary object with both the impaired and non-impaired arms, and showed more spatial variability towards the stationary target with only the impaired arm. Furthermore, a study by Lough (1985), described in Lee and Young (1986) illustrated that in hemiparetic stroke patients, movement of the impaired arm was improved (smoother with fewer sub-movements) when intercepting a moving ball (externally paced) compared to when intercepting a stationary ball (internally paced). Interestingly, however, there has also been some evidence that the timing constraints of externally paced tasks can improve performance of the impaired limb such that it approaches performance of the non-impaired limb. For example, Majsak et al. (1998) showed that although Parkinson's patients reached slower than healthy controls when the movement was self-determined (stationary ball), these differences disappeared without any loss of accuracy when the movements were externally paced (moving ball).

Clearly, then, at present there is good evidence that adults with movement disorders or disabilities are capable of adapting to the constraints imposed on them by their impairment (i.e., organismic constraints) as well as those of the task and the environment in which they perform (Archaumbault et al., 1999; Levin, 1996; Steenbergen et al., 2000). Although there has been some empirical work on children with SHCP or hemiparesis (Van der Weel et al., 1997), it has yet to be determined how such children adapt to the limitations of their action system when performing movement tasks in that are fundamental to functional behavior in everyday life. Therefore, the present study was designed to examine reaching and grasping behavior of children with SHCP in a behaviorally-realistic setting that imposed either internal or external timing constraints. Using this design, the present study addressed two questions. First, it examined whether the kinematics of reaching, and the coordination and recruitment of degrees of freedom, were modified when using the impaired arm compared to the non-impaired arm. Second, it determined how the reach response of the impaired and non-impaired arms was influenced by a task that required interception of a stationary object (internally paced) or an approaching object (externally paced).

Materials and Methods

Participants

Ten children with SHCP (mean age 8.6 years, *SD* = 1.8 years) participated in the experiment (Table 1). Both the children and their parents signed informed consent forms. The study was approved by the Regional Committee for Medical Research

Table 1 Participants Information

Participant	Diagnosis	Aetiology	Age (years)
1	Right spastic hemiparesis	CP: lack of O_2	7
2	Left spastic hemiparesis	CP: lack of O_2	10
3	Right spastic hemiparesis	CP: premature	5
4	Right spastic hemiparesis	CP: premature	9
5	Right spastic hemiparesis	Unknown	9
6	Left spastic hemiparesis	CP: lack of O_2	7
7	Right spastic hemiparesis	CP: lack of O_2	8
8	Right spastic hemiparesis	CP: lack of O_2	11
9	Left spastic hemiparesis	CP: premature	9
10	Left spastic hemiparesis	Unknown	11

Note. See text for explanation.

Ethics, Manchester, UK. Participants were UK residents and volunteered after parents were informed by an advertisement in the newsletter of Hemihelp.[1] Inclusion criteria were congenital spastic hemiparetic cerebral palsy, the ability to stand and walk independently, the ability to use the impaired arm, and age between 5–11 years. Exclusion criteria were ataxia, athetose, wheelchair dependency, and mental retardation. The participant information on the inclusion criteria was obtained by the parents informing the research team about the medical records (from the hospital or rehabilitation center) of each child. For five of the participants cerebral palsy was congenital, arising as a consequence of lack of oxygen at birth or by an infection. Three participants were part of twins and cerebral palsy was caused by a premature birth and for two participants the cause was unknown.

Procedure and Design

Participants were instructed to reach and grasp a ball with either their impaired or non-impaired arm. Table height was adjusted to the participant's body height, such that it was level with the end of the thumb when the arm was held vertically *beside* the table. The horizontal distance between the participant's hand in the start position and the ball was 30 cm, and the corresponding lateral distance was 10 cm. The ball was either stationary on the table (stationary ball condition) or rolled down an open tube of 1.5 m length (moving ball condition) (see Figure 1). The moving ball approached the participant *in front* with an average speed of 0.7 m/s and traveled on a path that brought it to the general vicinity of a marker located on the table (a blue circle of 10 cm diameter). In the stationary ball condition, the participants were instructed that they could commence their movement when the

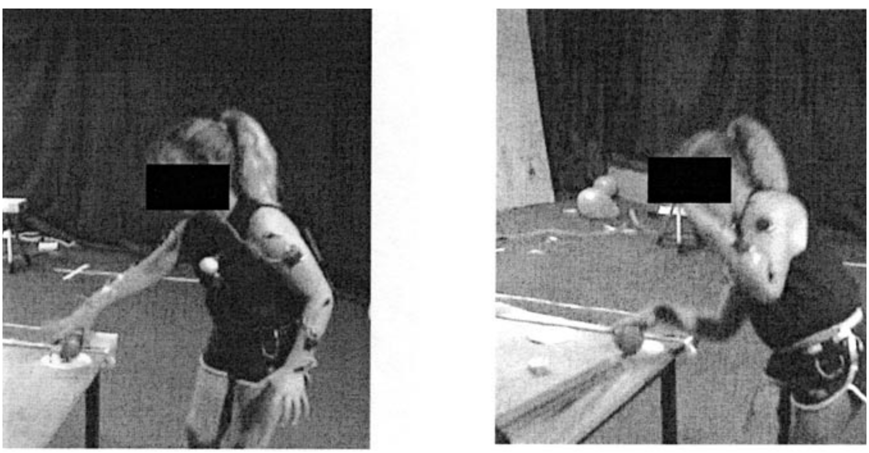


Figure 1—Reaching for a stationary ball (left) and reaching for a moving ball (right). In the moving ball condition the participant stands beside the table so the ball is really approaching the participant in front but moving towards one side of the participant.

[1] Hemihelp is a UK-based registry charity (since 1991) that provides information and support for children and young people with hemiplegia; it produces a quarterly newsletter (see www.hemihelp.org.uk).

experimenter gave an auditory starting signal. In the moving ball condition, the ball was released by the experimenter and participants were instructed that they could commence their movement only after the ball had been released. The participants had to catch the ball when it reached the blue circle on the table. Participants were asked to keep their arms beside their legs prior to commencing the reach and grasp. To become familiar with the task, participants performed three practice trials. When the task requirements were fully understood participants performed blocks of 15 trials with either their impaired arm or the non-impaired arm when the ball was either stationary or moving ($N = 60$). The order that trials were performed was counter-balanced across participants.

Apparatus

While performing a reaching and grasping movement, kinematic data was collected using a dual CODA mpx3 (Charnwood Dynamics, Rothley, UK) motion analysis system operating at a sampling frequency of 100 Hz. Data as the arm reached towards the ball was collected from markers placed on both sides of the body on the external face of the acromion processes of the shoulder, the lateral epicondyles of the humerus, and the styloid processes of the wrist. Data was also collected from markers placed on the sternum and on both the spina iliaca anterior superior (SIAS) of the pelvis and the spina iliaca posterior superior (SIPS) of the pelvis to determine the kinematics of the trunk.

Dependent Measures of Reaching Performance

Although the interceptive action performed in the present study consisted of both a reach and grasp phase, only the former was analyzed. A program was developed to identify key events in the displacement and velocity profiles of linear and angular data. Based on previous research on reaching in healthy children (Ricken, Savelsbergh, & Bennett, 2004) and children with cerebral palsy (Utley & Sugden, 1998; Volman et al., 2002) the following kinematic variables were extracted: peak velocity in the horizontal and vertical direction (PVX and PVY), movement time (MT), and deceleration time (i.e., time after peak wrist velocity until the moment of contact) in the horizontal and vertical direction (TAPVX and TAPVY). Trunk contribution was quantified by calculating the excursion of trunk lateral flexion, trunk flexion, and trunk rotation, where excursion is the sum of the angular change over time. These variables were calculated from the angle formed between the markers placed on the sternum, shoulder, and pelvis in a sagittal, transverse, and frontal plane. Trunk rotation is defined as the movement of the trunk in the transverse plane around the y-axis, trunk flexion is defined as the movement in the sagittal plane (x-y plane), and trunk lateral flexion is defined as the movement in the frontal plane (y-z plane) (see Figure 2). The elbow excursion, which consisted of both elbow flexion and elbow extension, was calculated from the resulting angle between the shoulder, elbow, and wrist markers. The shoulder excursion, which consisted of shoulder flexion and extension, and shoulder elevation and depression, was calculated from the resulting angle between the elbow and shoulder in the x-z plane and y-z plane (see also Figure 2).

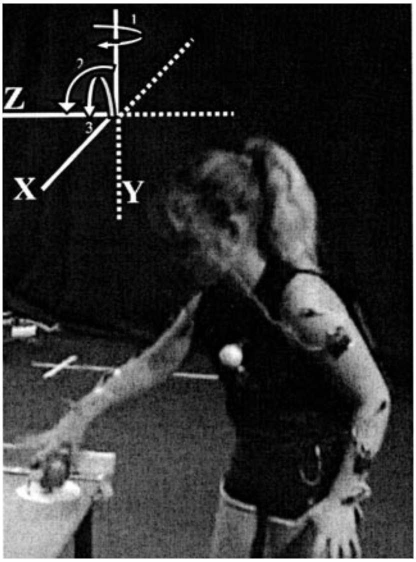


Figure 2—Definition of the planes and axes to determine the movements of the trunk, shoulder, and elbow. Sagittal plane is the *x*-*y* plane; frontal plane is the *y*-*z* plane and the transverse plane is the *x*-*z* plane. *X*-axis is the horizontal direction, *Y*-axis is the vertical direction and the *Z*-axis is the lateral direction. The arrows show the direction of the trunk movements: 1 = trunk rotation; 2 = trunk lateral flexion; 3 = trunk flexion. See also the explanation in the text.

Data Analysis

As SHCP is a disorder which primarily affects one side of the body, there is a unique opportunity to compare performance using the impaired arm to using the non-impaired arm within the same participant. This offers an advantage over the traditional approach of comparing SHCP children to non-SHCP children (a so-called control group) because it enables a direct, intra-participant comparison of movements performed with the impaired versus the non-impaired arm. This minimizes any random effects such as differences in the participant's motivation to take part in the experiment or the participant's interpretation of the task demands. In other words, the non-impaired arm can be used as a control by which to measure whether children with SHCP adjust their movement coordination and control when reaching for a stationary or approaching object.[2]

For each dependent measure, the intra-individual mean, standard deviation, and coefficient of variation were calculated for each condition, pooled across the

[2]Although sometimes the non-impaired side is also slightly affected, this does not pose a threat to internal validity of the experiment because the main focus of the study was to examine the reach response when using the non-impaired arm compared to the impaired arm, and how this is influenced by the task context. If a (healthy) control group had been used, it might be expected that the measures derived from the non-impaired and impaired arm of the SHCP children would differ from the control participants.

group and then submitted to separate 2-way repeated measures ANOVA: ball motion (stationary ball; moving ball) × arm (impaired; non-impaired arm). The intra-individual mean provides a measure of the average performance across trials for each level of independent variable, while the standard deviation and the coefficient of variation provide a measure of the variability in movement performance.

To express the level of coordination between joint pairs, the within trial cross-correlation coefficient was determined between elbow excursion and shoulder flexion, elbow excursion and shoulder elevation, and elbow excursion and trunk lateroflexion, for each individual-participant trial. The cross-correlation coefficient at zero time lag was calculated from time-normalized data (time series data were normalized to 100 data points by fitting a third order polynomial equation). The intra-participant mean and standard deviation of the *z*-transformed coefficients were calculated for each condition, pooled across the group and then submitted to separate 2-way repeated measures ANOVA: ball motion (stationary ball; moving ball) and arm (impaired; non-impaired arm).

To compare the linear relationship between two time series (e.g., elbow excursion and shoulder flexion), cross-correlation analysis has previously been used. The cross-correlation coefficient has been interpreted as a measure of changing recruitment of degrees of freedom, where higher values indicate tight joint couplings (more linear and less segmented coordination), and lower values indicate independent control (less linear and more segmented coordination; see McDonald, Van Emmerik, & Newel, 1989; Newell & Van Emmerik, 1989; Vereijken et al. 1992). Differences between the linearity of time series from joint pairs across independent measures (viz., different conditions) are then determined by ANOVA. An alternative technique for determining the correlation between two time series (e.g., elbow excursion and shoulder flexion) across independent measures (e.g., when performing in conditions of different object motion or using a different arm) was described by Sparrow, Donovan, Van Emmerik, and Barry (1987). The recognition coefficient, *R*, which is the peak value of the cross correlation between two separate angle-angle plots, is sensitive to the size, shape, and orientation and is therefore a good measure of (dis)similarity between two coordination patterns. R ranges from 0 to 1.0 according to the degree of similarity, such that as *R* approaches zero, the angle-angle plots become increasingly dissimilar in shape. We used this technique to determine the (dis)similarity between individual participant's coordination as a function of object motion and arm. To this end, we calculated the recognition coefficient *R* between the individual participant's mean elbow excursion/shoulder flexion, elbow excursion/shoulder elevation, and elbow excursion/trunk lateroflexion, when reaching: (a) with the non-impaired arm for the stationary ball versus the moving ball; and (b) with the impaired arm for the stationary ball versus the moving ball. The resulting *R* coefficients were *z*-transformed, pooled across participants and submitted to two-tailed *t*-test.

Results

The results are presented in three sections. In the first, main effects from the analysis of the discrete kinematic variables are presented (there were no significant interaction effects). The second section presents the quantitative analysis of the joint relationship using the cross-correlation technique, and the third section describes the direct analysis of the (dis)similarity between two coordination patterns (angle-angle plots) as a function of ball motion and arm.

Kinematics of Reaching

Movement Time, Deceleration Time, and Peak Velocity. A significant main effect of movement time [$F(1, 9) = 5.32$, $p < .05$] and vertical deceleration time [$F(1, 9) = 5.11$, $p < .05$] was noted for arm. Participants reached with a longer movement time and a longer vertical deceleration time when using the impaired arm compared to non-impaired arm. For the horizontal and vertical deceleration time a significant main effect was found for ball [$F(1, 9) = 8.08$, $p < .05$ and $F(1, 9) = 4.64$, $p < .05$]. Participants exhibited a longer horizontal and vertical deceleration time when

Table 2 Means of Dependent Variables (SD in parentheses) as a Function of Condition and Arm

	Standing—stationary ball		Standing—moving ball	
Variable	Impaired	Non-impaired	Impaired	Non-impaired
Movement time (s)	1.18 (0.37)	0.96 (0.25)	1.03 (0.37)	0.81 (0.32)
TAPVX (s)	0.68 (0.33)	0.52 (0.21)	0.42 (0.19)	0.29 (0.14)
TAPVY (s)	0.88 (0.30)	0.68 (0.15)	0.65 (0.21)	0.56 (0.27)
PVX (m/s)	0.32 (023)	0.25 (0.21)	0.40 (0.16)	0.46 (0.20)
PVZ (m/s)	0.49 (0.14)	0.53 (0.18)	0.45 (0.17)	0.53 (0.25)
Trunk rotation (deg)	21.22 (9.95)	15.24 (7.82)	19.43 (11.72)	13.77 (5.81)
Trunk flexion (deg)	18.92 (15.30)	15.76 (20.26)	14.74 (8.28)	10.25 (9.76)
Trunk latero-flexion (deg)	29.11 (25.38)	9.86 (9.81)	35.14 (29.25)	15.35 (11.42)
Elbow excursion (deg)	69.71 (24.95)	79.31 (22.10)	59.57 (17.24)	73.01 (20.19)
Shoulder flexion (deg)	26.78 (11.89)	31.84 (19.03)	25.83 (10.71)	29.63 (8.5)
Shoulder elevation (deg)	11.24 (6.46)	8.32 (4.99)	18.12 (14.69)	9.77 (5.90)

Note. TAPVX, time after peak velocity in horizontal direction; TAPVY, time after peak velocity in vertical direction; PVX, peak velocity in horizontal direction; PVY, peak velocity in vertical direction.

reaching for the stationary ball compared to moving ball (see also Table 2). No significant main effects of arm were found for the variable peak velocity.

Angular Excursion. Significant main effects were found for arm, with participants exhibiting a reduced elbow excursion [$F(1, 9) = 8.3$, $p < .05$), accompanied by an increased trunk rotation [$F(1, 9) = 5.92$, $p < .05$] and trunk lateroflexion [$F(1, 9) = 9.504$, $p < .05$], when reaching with the impaired arm (see also Table 2).

There was a significant main effect of arm for the standard deviation of trunk rotation [$F(1, 9) = 6.77$, $p < .05$] and trunk lateral flexion [$F(1, 9) = 7.32$, $p < .05$], and for the coefficient of variation of shoulder flexion [$F(1, 9) = 8.71$, $p <0.05$]. There were no significant differences in the standard deviation or coefficient of variation data for any of the other discrete measures (PVX, PVY, TAPVX, TAPVY, trunk flexion, shoulder elevation, elbow flexion, and movement time).

Coordination Between Joint Pairs

Cross-correlation Coefficients. There were no significant main effects of ball for the cross-correlation analysis (intra-participant mean or *SD*). There was, however, a main effect of arm [$F(1, 9) = 5.63$, $p < .05$] for the intra-participant mean cross-correlation coefficients of elbow excursion/shoulder flexion. Observation of the individual participant data (see Table 3) indicated that the majority of participants exhibited lower cross-correlation coefficients, and hence a less linear coordination between elbow excursion and shoulder flexion when reaching with the impaired arm compared to the non-impaired arm. Two participants (4 and 5) exhibited the reverse trend in both the stationary ball and moving ball conditions.

Recognition Coefficients. For the (dis)similarity of the individual participant's mean coordination within the stationary ball compared to moving ball conditions, *t*-test analysis revealed a significant difference between the impaired arm and non-impaired arm for elbow excursion/shoulder flexion [$t(18) = -2.5$, $p = .02$] and elbow excursion/shoulder elevation [$t(18) = -2.1$, $p = .04$]. For the majority of participants (see Table 4) these joint pairs were coordinated with more similarity in the stationary ball compared to moving ball conditions when reaching with the non-impaired arm. For the (dis)similarity of the individual participant's mean coordination when reaching with the impaired arm compared to non-impaired arm, *t*-test analysis revealed no significant differences between the stationary ball and moving ball conditions.

The origin of the difference in (dis)similarity between the coordination of elbow excursion against shoulder flexion for the impaired and non-impaired arm can be seen in Figure 3, which shows a representative example from one participant. Here it can be seen that the plot of elbow excursion against shoulder flexion is more similar when using the non-impaired arm to reach for either a stationary (panel A) compared to a moving ball (panel C), than when using the impaired arm to reach for a stationary (panel B) and moving ball (panel D). Participants started to move their non-impaired arm with elbow flexion and simultaneous shoulder extension, after which elbow extension was increased with a similar amount of shoulder flexion (panels A and C). For the impaired arm there was a far less symmetric pattern of elbow flexion and shoulder extension, followed by elbow extension and shoulder flexion (panels B and D).

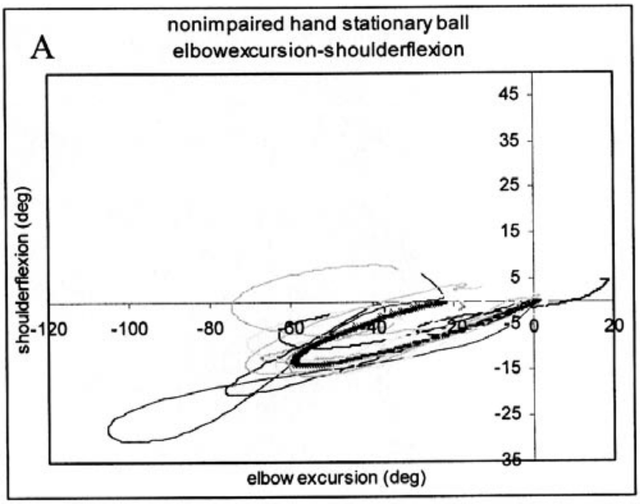
Table 3 Individual-Participant Means (SD in parentheses) of Cross-Correlation Coefficients as a Function of Ball Motion and Arm

		Stationary ball		Moving ball	
Joint relationship	Partici-pant	Impaired	Non-impaired	Impaired	Non-impaired
Elbow excursion—Shoulder flexion	1	0.37 (0.30)	0.76 (0.25)	0.54 (0.23)	0.58 (0.29)
	2	0.51 (0.27)	0.93 (0.07)	0.45 (0.28)	0.93 (0.06)
	3	0.39 (0.15)	0.69 (0.12)	0.51 (0.36)	0.63 (0.19)
	4	0.67 (0.25)	0.52 (0.27)	0.58 (0.29)	0.48 (0.20)
	5	0.75 (0.11)	0.69 (0.19)	0.71 (0.17)	0.45 (0.28)
	6	0.34 (0.30)	0.52 (0.14)	0.39 (0.27)	0.56 (0.28)
	7	0.58 (0.16)	0.77 (0.24)	0.79 (0.21)	0.74 (0.24)
	8	0.84 (0.14)	0.83 (0.25)	0.77 (0.26)	0.91 (0.10)
	9	0.38 (0.33)	0.80 (0.20)	0.55 (0.23)	0.59 (0.27)
	10	0.54 (0.29)	0.94 (0.07)	0.50 (0.32)	0.79 (0.13)
Group mean		0.54 (0.23)	0.75 (0.18)	0.58 (0.26)	0.67 (0.20)
Elbow excursion—Shoulder elevation	1	0.53 (0.26)	0.50 (0.32)	0.77 (0.12)	0.30 (0.22)
	2	0.29 (0.30)	0.23 (0.18)	0.48 (0.39)	0.53 (0.21)
	3	0.73 (0.21)	0.75 (0.22)	0.46 (0.24)	0.44 (0.28)
	4	0.80 (0.17)	0.24 (0.26)	0.51 (0.32)	0.27 (0.24)
	5	0.60 (0.28)	0.34 (0.24)	0.42 (0.26)	0.41 (0.28)
	6	0.58 (0.17)	0.62 (0.24)	0.66 (0.32)	0.60 (0.27)
	7	0.72 (0.30)	0.28 (0.21)	0.42 (0.19)	0.25 (0.14)
	8	0.40 (0.19)	0.61 (0.33)	0.46 (0.25)	0.48 (0.32)
	9	0.60 (0.32)	0.80 (0.20)	0.43 (0.32)	0.51 (0.25)
	10	0.73 (0.19)	0.87 (0.10)	0.53 (0.21)	0.31 (0.21)
Group mean		0.60 (0.24)	0.52 (0.23)	0.51 (0.26)	0.41 (0.24)
Elbow excursion—Trunk lateral flexion	1	0.38 (0.23)	0.50 (0.24)	0.73 (0.12)	0.30 (0.18)
	2	0.29 (0.31)	0.32 (0.24)	0.52 (0.36)	0.55 (0.22)
	3	0.67 (0.28)	0.45 (0.31)	0.40 (0.27)	0.29 (0.21)
	4	0.47 (0.29)	0.42 (0.31)	0.44 (0.34)	0.51 (0.20)
	5	0.59 (0.30)	0.25 (0.22)	0.37 (0.20)	0.54 (0.21)
	6	0.52 (0.34)	0.44 (0.25)	0.52 (0.22)	0.50 (0.27)
	7	0.40 (0.11)	0.58 (0.13)	0.53 (0.16)	0.28 (0.20)
	8	0.50 (0.30)	0.64 (0.23)	0.48 (0.28)	0.61 (0.28)
	9	0.32 (0.21)	0.40 (0.24)	0.39 (0.32)	0.45 (0.23)
	10	0.45 (0.37)	0.46 (0.34)	0.31 (0.23)	0.32 (0.28)
Group mean		0.46 (0.27)	0.45 (0.25)	0.47 (0.25)	0.44 (0.23)

Table 4 Individual-Participant Recognition Coefficients for the Comparison of Two-Joint Coordination in the Stationary and Moving Ball Condition, When Reaching with the Impaired and Non-Impaired Arm

	Participant	Impaired stationary vs moving ball	Non-impaired stationary vs moving ball
Elbow flexion-shoulder flexion	1	0.22	0.33
	2	0.31	0.41
	3	0.53	0.56
	4	0.27	0.52
	5	0.46	0.33
	6	0.33	0.68
	7	0.30	0.46
	8	0.26	0.40
	9	0.19	0.62
	10	0.48	0.39
Group mean		0.34	0.47
Elbow flexion-shoulder elevation	1	0.15	0.32
	2	0.36	0.42
	3	0.51	0.52
	4	0.23	0.49
	5	0.44	0.37
	6	0.46	0.48
	7	0.27	0.45
	8	0.31	0.42
	9	0.25	0.61
	10	0.48	0.38
Group mean		0.35	0.45
Elbow flexion-trunk lateral flexion	1	0.28	0.33
	2	0.37	0.41
	3	0.52	0.52
	4	0.21	0.48
	5	0.44	0.32
	6	0.61	0.55
	7	0.27	0.44
	8	0.29	0.38
	9	0.24	0.66
	10	0.45	0.38
Group mean		0.37	0.45

Note. A higher value indicates a more similar coordination pattern.



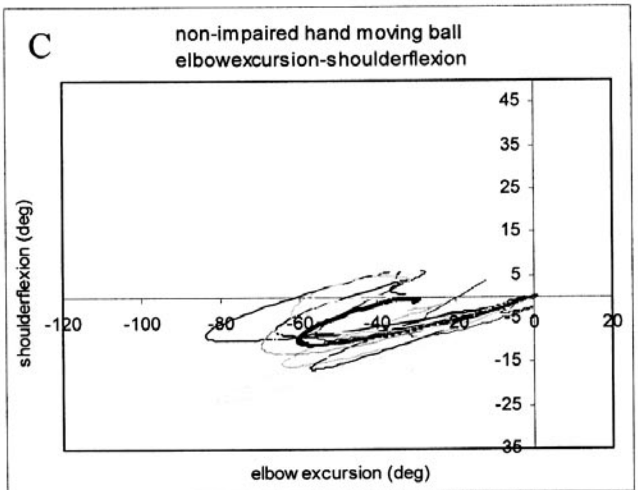


Figure 3—Representative illustration of one participant of the angle-angle plots (elbow excursion against shoulder flexion) as a function of ball motion (stationary ball; moving ball) and arm (impaired; non-impaired). The thick line shows the mean of all individual trials (as presented by the thin lines). For clarity, the time series have been normalized to a start position of zero. The recognition coefficients calculated by using the mean plots of Figures 3A and 3C, were *t*-tested to the recognition coefficients calculated by using the mean plots of Figures 3B and 3D.

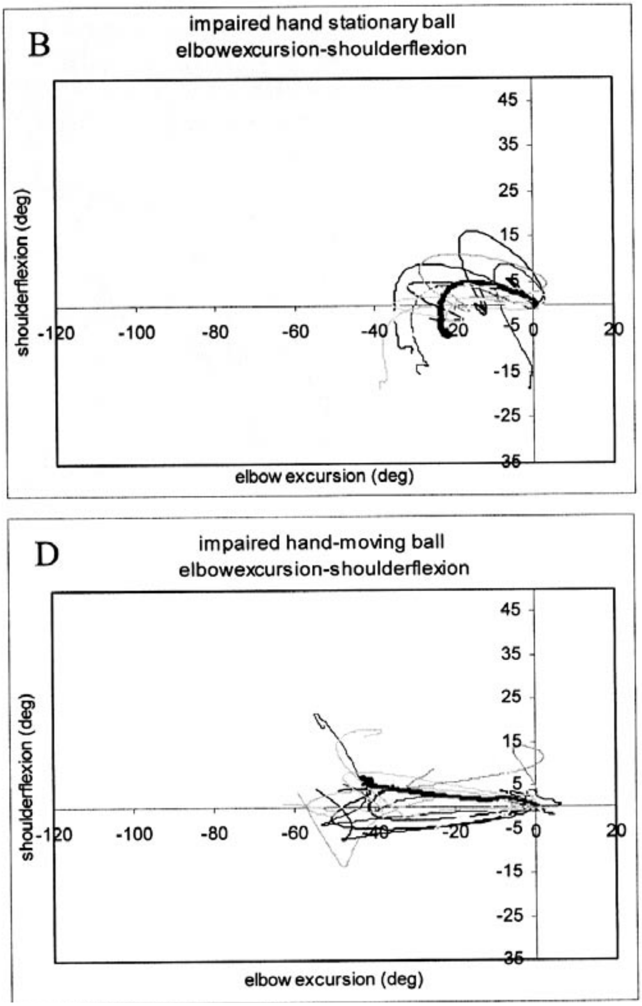


Figure 3—(continued)

Discussion

Following on from research with adult participants with SHCP, and motivated by the lack of work on children with SHCP, the present study was designed to examine reaching and grasping behavior of children with SHCP in a behaviorally-realistic setting that imposed either internal or external timing constraints. Using intra-participant comparisons in which each participant acted as their own control, we examined: (a) if the kinematics of reaching, and the coordination of degrees of freedom, was modified when using the impaired arm compared to the non-impaired arm; and (b) how the reach response of the impaired and non-impaired arms was influenced by a task that required interception of a stationary (internally paced) or an approaching (externally paced) object.

Consistent with previous work with adults (Archaumbault et al., 1999; Levin, 1996; Steenbergen et al., 2000), it was found that children with SHCP used a different movement strategy when reaching with the impaired arm compared to the non-impaired arm. This was achieved by a prolonged movement time and deceleration time and an increased trunk contribution, which might be related to the decreased elbow and shoulder excursion. The effect of the impairment was also evident in the continuous measures of joint coordination. Participants reached with a less linear and hence more segmented coordination of elbow excursion and shoulder flexion when using the impaired compared to non-impaired arm. In addition, we found that the similarity of coordination was influenced by the arm used. Participants exhibited less similar coordination between elbow excursion and shoulder flexion, and elbow excursion and shoulder elevation in the stationary ball compared to the moving ball condition when reaching with the impaired rather than non-impaired arm. In other words, although participants maintained a similar type of coordination in the stationary and moving ball conditions when reaching with the non-impaired arm, they did not maintain the same coordination across the different task contexts when reaching with the impaired arm.

When the task context was externally paced and participants reached for a moving ball, there was less obvious modification to the discrete kinematic measures. Contrary to previous work with healthy children (Ricken, Savelsbergh, & Bennett, 2004), who deal with the impact demands of an approaching object by lengthening deceleration time and movement time, we found that children with SHCP exhibited a reduced deceleration time in the moving ball condition compared to the stationary ball condition. At present it is not clear why we observed these differences in the timing of the reaching movement. Future work is required to determine if this occurred because children with SHCP were less able to perceive the impact requirements of the moving ball condition or if they modify their response accordingly. Interestingly, we also did not replicate the finding that the timing constraints of externally paced tasks can improve performance of the impaired limb compared to that of internally paced tasks, as was reported for Parkinson patients (Majsak et al., 1998). Perhaps this difference in reported findings indicates that it is the persistent spasticity of CP that cannot be overcome. Children with SHCP were capable of organizing movement solutions within their own action capabilities, but the effect of the impaired side of the body was not fully overcome by modifying the timing constraints (see also Van Thiel et al., 2000). Future work is required to examine if this inability to improve performance of the impaired limb to the level of the non-impaired limb remains when performing under more challenging timing constraints, such as reaching for a moving ball while the participant is walking. As participant information in the present study was rather restricted, in future research this could be further explored and possibly linked to scores obtained from tests on spasticity, dexterity, or severity (for example, Fugl-Meyer or Ashworth spasticity scores).

To summarize, children with SHCP used a movement strategy that compensated for their impaired arm, enabling them to successfully adapt their reach response to the impact requirements of the different conditions. Still, regardless of the timing constraints imposed by the task context, children with SHCP did not adopt a similar response when reaching with the non-impaired and impaired arm.

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